TECHNICAL REPORT
70-6-CE

AD 695043

DEVELOPMENT OF
LIGHTWEIGHT INSULATED FOOTWEAR

by
Joseph E. Assaf

July 1969

Clothing and Personal Life Support Equipment
Laboratory
C&PLSEL-67

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Project Reference:
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Clothing and Personal Life Support Equipment Laboratory
U.S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760

FOREWORD

The thermal adequacy of the present 40-ounce standard black insulated Army boots for cold-wet use has been validated by actual experience. However, studies indicate that, in reference to energy consumption, one ounce carried on the foot is equivalent in weight to six ounces carried on the back (30-pound equivalent). In view of this, the development of new lightweight materials for insulated footwear is essential. The boots should be in the weight range of 15 to 20 ounces per boot and offer environmental protection at temperatures as low as -20°F. The U.S. Army Natick Laboratories (NLABS) determined to meet this objective through advances made in materials technology and by the development of new design criteria and processing techniques.

This report summarizes the work performed toward the development of lightweight (15-20 oz per boot), impermeable (water absorption maximum weight gain 5%), insulated footwear (for service down to -20°F for periods up to 2 hours of inactivity). Under the guidance of the author as Project Officer, the materials and fabrication studies, including the manufacture of 150 pairs of lightweight insulated footwear, were performed by Uniroyal, Inc., under Contracts #DA19-129-AMC-690(N) and DA19-129-AMC-959(N). The copper foot calorimeter studies and the low temperature chamber evaluations were conducted by the U.S. Army Natick Laboratories.

The author is especially grateful for the invaluable suggestions of E. I. Du Pont Company Elastomers Chemicals Group resulting in the development of the expanded polyurethane sole with a solid outer skin.

The author also wishes to acknowledge the aid and guidance of Mr. Douglas Swain, Footwear Technologist at NLABS, relative to design considerations, and of Dr. Herman Thies, Consultant. He wishes to thank Dr. Ralph F. Goldman and Mr. John Breckenridge of the U.S. Army Research Institute of Environmental Medicine (ARIEM), a tenant activity at Natick, for conducting the copper foot calorimeter studies and for their valued suggestions; and Mr. Edwin Zelezny and Mr. John Arbacchuk of NLABS for assistance in the Climatic Chamber studies.

The work was conducted under Project Number 1J662708D504, Individual Combat Protective Clothing and Equipment, Exploratory Development.

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ABSTRACT

The feasibility of producing the first generation of military lightweight insulated footwear using selected materials in a basic pull-on type construction in the weight range of 15-20 ounces per boot was demonstrated. The fabrication of the boots was achieved by two different approaches: (1) by conventional fabrication techniques using the minimum possible number of components; (2) by integrally casting or expanding in place a boot of unified construction. Two prototypes of 50 pairs each were produced on a semi-production basis by conventional fabrication methods. One prototype used expanded closed-cell polyethylene for upper insulation; the other used expanded closed-cell polyurethane from a millable gum for upper insulation.

An additional prototype of 50 pairs was produced by the newly-developed integrally casting technique using liquid polyurethane pre-polymers. This technique of producing expanded polyurethane insulated footwear offers the greatest potential of meeting the requirements of a lightweight (15-20 ounces per boot), impermeable (water absorption maximum weight gain 5%), insulated (for service down to -20°F) boots for up to two hours of inactivity. The integrally cast expanded polyurethane footwear (18-20 ounces per boot), when new, approaches the insulative performance of the standard (black 40-43 ounces per boot) cold-wet boot, but may have reduced durability and service life.

DEVELOPMENT OF LIGHTWEIGHT INSULATED FOOTWEAR

1. Introduction

Preliminary studies under the program, Exploratory Development in Support of Combat Clothing Systems indicated the feasibility of providing lighter weight insulated boots without significantly decreasing the effectiveness of the insulation value. Therefore, materials research studies were initiated to develop new lightweight materials to be used as components or groups of components for lightweight insulated footwear in the weight range of 15 to 20 ounces per boot. The proposed insulated footwear was also to be impermeable (water absorption maximum weight gain 5%) and offer maximum environmental protection down to -20°F, for periods up to two hours of inactivity. This research was particularly significant when related to the system projected to lighten the weight of clothing and equipment for the combat soldier (LINCLOE).

To achieve a significant reduction in weight, it was necessary to make full use of advances made in materials technology since the development of the standard black insulated U.S. Army boot which was designed for cold-wet wear. The black insulated footwear weighs approximately 40 ounces per boot. In reference to energy consumption of the combat soldier, studies indicate that one ounce of weight carried on the foot is equivalent to 6 ounces carried on the back (two 40-ounce boots are equivalent to 30 pounds) of the combat soldier.

2. Development of Current Standard Insulated Footwear

The principle of the current standard boot was conceived during World War II. The resultant development of design and fabrication methods saw the production of insulated footwear for use in the Korean War. For the first time a soldier's feet were protected from cold injuries under cold-wet field conditions.(1)

The results of continual modifications and improvements in materials, design and fabrication techniques since the Korean War are evidenced in the requirement for an insulated boot for cold-wet use which conforms to Type I, Class 1, Rigid Sole of Military Specification MIL-B-41816A Boots, Insulated, Cold-Weather, Rubber, dated 15 March 1965. This boot was designed to protect feet from cold injury and frostbite in areas where moisture and cold are critical factors, where the mean monthly temperature ranges between 14°F and 68°F and where temperatures do not fall below -20°F.

The physical properties and the thermal adequacy of the black insulated boot for cold-wet use (service down to -20°F) have been validated by actual field experience. These properties were achieved at the expense of bulk and weight - each boot weighs 40-43 ounces.

The wool fleece now used in the standard insulated boot provides satisfactory insulation in undamaged boots; however, when boots are damaged, the fleece absorbs moisture, resulting in a rapid loss of insulating properties. If the boots become damaged, patching kits are available to prevent leakage of moisture into the insulation.

Efforts were made to increase the efficiency of the standard insulated black boot by increasing the reliability of the insulation through the use of non-wettable types of cellular materials. These attempts to increase the reliability of the insulation by use of cellular materials within the present design concept of the standard boot did provide a more constant level of insulation; however, the results were negated by increased stiffness and poor resistance to compression set of the cellular materials. The footwear was considered uncomfortable and difficult to don and doff at low temperatures. In addition, problems were encountered in packaging and storing at low temperatures.

Additional efforts were expended to reduce the weight of the boot while retaining the required insulation by removal of some of the marginal components and by attempting to reduce the weight of other boot components. The weight reduction achieved was negligible.

These studies indicated that conventional footwear materials and design have only limited promise for achieving the required weight reduction without an undesirable loss of physical and thermal properties.

3. Phase I - Materials and Design Studies

The program was divided into two phases. The first 12-month phase(2) was primarily for materials research studies. Some studies relating to simulated constructions and conceptual design studies of a complete footwear system were conducted to insure that the newly developed materials could be formed into the shape of a boot. The second phase, covering a period of 18 months, saw the refinement of materials selected from the first phase, the preparation of prototypes from the developed design concepts, and the production of 150 pairs of lightweight insulated footwear in three constructions.(3)

Materials evaluated included expanded rubbers, thermoplastic foams, rigid foams, fibrous materials, special impermeable materials for outer finishes and other auxiliary materials.

In addition, basic design studies were conducted utilizing materials selected as a result of the materials evaluation, including studies of simulated constructions, and the fabrication of footwear.

a. Materials Studies

To insure that the most promising materials were selected for evaluation, a literature search was conducted. The selected candidate materials were compounded, tested, and evaluated with an aim toward achieving lightweight insulating materials. During the materials studies, attempts were made to combine sections of the footwear so that the resulting product would have as few components as possible. To outline the original candidate materials selected for study, the nomenclature for components found in conventional footwear was used. The candidate materials selected were:

(1) Outsoles/Midsoles/Insoles

Expanded EPDM (ethylene-propylene terpolymer)
Expanded CR (neoprene)
Expanded NBR (nitrile-butadiene)
Expanded IIR (butyl rubber)
Expanded CSM (chlorosulfonated polyethylene)
Expanded PVC/NBR (polyvinyl chloride/nitrile-butadiene)
Expanded polyurethane
Expanded polyethylene

(2) Shank Supports

Stainless steel
Hard aluminum alloy
ABS (acrylonitrile-butadiene-styrene)
Acetal plastic
Nylon plastic
Polycarbonate plastic

(3) Reinforcements for Counters and Toe Caps

Semi-rigid expanded ABS (acrylonitrile-butadiene-styrene)
Rigid expanded ABS (acrylonitrile-butadiene-styrene)
Impregnated woven nylon fabric
Impregnated woven glass fabric
Impregnated woven polyester fabric
Impregnated non-woven nylon fabric
Impregnated non-woven glass fabric

(4) Reinforcement for Vamp and Liner

Nylon fabrics
Polyester fabrics

(5) Exterior Coating

Polyurethane
IIR (butyl rubber)
EPDM (ethylene-propylene terpolymer)
CSM (chlorosulfonated polyethylene)
IM (polyisobutene)

(6) Insulation

The same candidates as for outsoles

(7) Auxiliary Components

Design considerations will determine selection of materials for boot closures.

(8) Adhesives

Adhesives to be developed will be compatible with the selected materials.

Using the selected materials for the major footwear components, compounding studies were conducted, cure-time-temperature relationships were evaluated, processing techniques were developed, and the most suitable compounds were then subjected to a selected series of physical tests. The selected materials for the remaining footwear components, such as the vamp, sock lining and shank support, were also evaluated in a selected series of physical tests.

The initial screening test was conducted to significantly reduce the number of candidates prior to initiation of an extensive testing program. The final candidate material selection was dependent upon the special physical characteristics required for key functional areas of insulated footwear when related to their requirements for thermal insulation, density, abrasion resistance, low temperature flexibility, water absorption, compression set, and aging during long-term storage. In addition, the materials selected for basic design and fabrication studies had to be capable of being formed and fabricated into insulated footwear without the use of complex and costly fabricating techniques.

The chosen materials listed in order of preference were as follows:

Outsole/Midsole/Insole	Density (lbs/cu/ft)
Expanded polyurethane*	22-27
Expanded neoprene	22-27
Expanded ethylene-propylene terpolymer	22-27
Insulation	
Expanded polyethylene*	3-3.5
Expanded neoprene	6-7
Expanded ethylene-propylene terpolymer	5-6

* The expanded materials are closed-cell, chemically blown.

Counter/Toe Cap	
Expanded rigid ABS	10-14
Vamp/Liner	(oz/sq/yd)
Plain woven polyester fabric	3.3
Plain woven nylon fabric	3.3
Exterior Coating	
Polyether polyurethane	about 13½
Butyl rubber	about 24
Neoprene	about 25
Adhesives	
Nitrile base	
Neoprene base	

b. Discussion of Final Candidate Materials Selection

Outsole/Midsole/Insole - A polyurethane (polyether type) compound exhibited the best properties, including ease of mold design, and was the prime candidate. Alternate candidates were neoprene and ethylene propylene terpolymers. If it should become necessary to consider neoprene, additional studies would have to be conducted to improve compression set by resin reinforcement. The ethylene-propylene terpolymers would require additional studies to overcome adhesion problems. It may also be difficult to mold a traction design in a neoprene or ethylene-propylene outsole because of the complex techniques necessary for blowing of these materials. It is anticipated that the final density of the outsole/midsole/insole combination will be in the range of 24 ± 4 pounds per cubic foot.

Shank Support

Stainless steel
Hard aluminum alloy
Rigid acetal

These materials were selected based upon their flex life and weight per unit area. The final selection will be based upon the results of design studies and construction techniques developed.

Exterior Coating - May be of spray type. Polyurethane, polyether and polyester types were prime candidates. The final selection will be based upon the construction techniques developed. Neoprene and butyl were the alternate candidates.

Upper Insulation - Open cell materials were ruled out because of reduced flexibility upon application of the outer impermeable skin. In addition, the finished material, when folded, takes on a permanent crease. Therefore, the insulation values of these materials were not determined. Compounding studies at this point indicated that the current state of the art does not permit the production of a true closed-cell, low-density (4.5 lb/ft^3 and lower) polyurethane. The low-density polyurethanes developed have high moisture absorption rates.

An analysis of the data developed showed that expanded low-density polyethylene was the prime candidate for upper insulation, with neoprene and ethylene-propylene terpolymer as the alternate materials.

Counter and Toe Cap - Rigid ABS (acrylonitrile-butadiene-styrene), was chosen as the single candidate because of its low density and thermal conductivity.

Vamp/Liner - Plain woven polyester was the prime candidate because of good abrasion resistance, good tensile strength and low water absorption. A plain woven nylon was the second choice.

Adhesives - The final selection was based upon materials, design and construction considerations. A neoprene-base adhesive and a nitrile-base adhesive were selected.

c. Design and Fabrication Considerations

To determine the areas where the greatest weight reduction may be achieved and which footwear components may be combined or eliminated, the weights of the component parts of the present standard black insulated boot (approximately 44 components) were obtained (Table I).

TABLE I

WEIGHTS OF COMPONENT PARTS OF
STANDARD BLACK INSULATED BOOT

Component Number	Component	Weight (grams)
1	Inner lining sealer	62.600
2*	Nylon liner lining) (two per boot)	29.870
2	Nylon inner lining)	26.923
3*	Inner lining seal strip	5.619
4	Inside friction vamp	14.780
5	Inside toe stiffener	4.197
6	Friction filler	23.959
7	Heel stiffener	21.263

TABLE I (Cont'd)

Component Number	Component	Weight (grams)
8	Inside friction counter	9.828
9	Inner vamp lining	30.541
10	Inner quarter lining	31.073
11	Inside toe cap	6.243
12	Midsole shank unit (not impregnated)	160.000
12	Midsole shank unit (impregnated)	196.000
13	Outer vamp lining	33.326
14	Outer quarter lining	54.985
15*	Vamp sealer	26.941
16	Quarter sealer	73.991
17	Friction sole form	15.787
18	Combination vamp and chafing piece	14.568
19*	Upper	115.360
20	Heel stay	9.470
21	Friction toe foxing	15.756
22	Gum toe foxing	25.420
23	Friction heel piece	18.765
24	Gum heel piece	34.842
25	Lace chafing piece	6.267
26	Eyelet stays (this weight includes 26 through 31 assembled) (two per boot)	36.785
27	Eyelet stay cover (this weight includes 27 through 31 assembled) (two per boot)	37.251
28	Eyelet stay form) (two per boot)	9.349
28	Eyelet stay form)	9.57
29	Outer eyelet stay) (two per boot)	6.163
29	Outer eyelet stay)	6.018
30	Inner eyelet stay) (two per boot)	4.185
30	Inner eyelet stay)	4.389
31	Hinge stay) (two per boot)	0.512
31	Hinge stay)	0.508
32	Toe cap	8.288
33	Outside sole form	9.916
34	Outsole	153.000
34	Heel	129.000
35*	Outsole wedge	10.521
36*	Outsole bind	16.352
37	Ski strap shelf	3.167
38	Valves	4.367
39	Valve stay	1.443
40	Valve base anchor	.701
41	Eyelets (12 eyelets and 12 reinforced washers)	4.743
42	Lacing	7.262

TABLE I (Cont'd)

Component Number	Component	Weight (grams)
43	Rubber label	.415
44	Rubber label	.313

* These weights include the excess material that will be removed during the finishing and trimming operations.

The component parts are described under para. 3.6 of MIL-B-41816, Boots, Insulated, Cold Weather, Rubber conforming to Type I, Class 1 for cold-wet use. These parts are not necessarily presented in the order of fabrication. The total gram weight of the component parts is 1,334.901 grams or 47 ounces. The total overall weight represents the total weight of one boot, prior to trimming and finishing. A finished boot fabricated in accordance with the requirements of the specification will weigh approximately 40-43 ounces.

Data analysis at this time in the development cycle was essentially a matter of judgment. However, at this stage in the materials development, design fabrication studies were required to determine whether the selected experimental materials could be formed and fabricated into prototype boots. In addition, the prototype boots would allow the determination of the insulating properties of the materials in combination with each other.

Based upon the weights obtained on the standard insulated boot components, the two key areas for potential weight reduction appeared to be in the sole and heel and in the elimination of the numerous layers of materials used in the upper part of the boot.

The prime functional and design considerations were as follows:

(1) Minimum weight and bulk,

(2) Ease of donning and doffing,

(3) Combining, if possible, outsole, midsole, insole into one section,

(4) Determining the insulation value required to compute total thickness of the outsole, midsole, insole combination,

(5) Providing maximum traction in outsole, and

(6) Considering the overall functional capabilities for over-snow equipment, marching and in operating military vehicles.

The ultimate goal of producing the required footwear would be the simultaneous molding in one step of all of the footwear components into one complete boot. Consideration was given to this approach of producing a boot in one operation. However, it was determined that the materials and technical know-how had not yet been developed to insure the feasibility of producing footwear by this method. Therefore, initial fabrication efforts would be accomplished by conventional methods of "laying-up" the components on a footwear last and combining parts by the use of adhesives. The fabrication of prototype boots would allow the determination of the insulating properties of the materials in combination with each other.

It was anticipated that gusset and zipper or other exposure-type construction would reduce the degree of reliability and expose the boot to failure during use, increase weight, and result in complex fabricating techniques to insure proper maintenance of insulating properties. Therefore, to determine the feasibility of achieving the performance objectives, a basic pull-on type construction with a minimum number of components was selected as the starting point for fabricating boots. If fastening and closure devices had to be considered, they would be kept as simple as possible.

It was recognized that a reduction in the weight and bulk from that of the current standard black insulated boot might reduce the durability and service life, but that it might be possible to achieve equivalent insulating properties. To arrive at permissible weights for the major components and to determine the finished boot weights using the most promising material combinations, basic design configurations were developed. The primary candidate materials selected for fabrication were as follows:

(1) <u>Outsole, midsole, insole</u> - all polyurethane at 24 lb/cu/ft.

(2) <u>Upper insulation</u> - expanded polyethylene at 3.1 lb/cu/ft and 1/8 inch thick.

(3) <u>Sock lining</u> - 3.3 oz/sq/yd fabric.

(4) <u>Vamp</u> - 3.3 oz/sq/yd fabric.

(5) <u>Exterior coating</u> - polyurethane spray coating at 0.015 inches thick.

(6) <u>Counter and toe cap</u> - rigid ABS at 12.9 lb/cu/ft and .030 inches thick.

(7) <u>Shank support</u> - stainless steel at 11.61 grams/sq/in.

Based upon the design configuration developed, and the computation of the weight of each component, a tabulation of the finished weight of a hypothetical boot was as follows:

Component Parts	Weight (ounces)
Soles	4.35
Insulation	0.74
Liner	0.60
Vamp	0.11
Exterior	2.39
Counter and Toe Cap	0.60
Shank Support	0.41
Total boot weight	9.20

These figures do not take into consideration the use of adhesives, reinforcement strips, fasteners, or any other changes such as design or increase in weight of materials for insulation purposes and durability that may be required as a result of fabrication studies and testing. It should be recognized that this is the ultimate that can be achieved, and if a completed boot meeting all of the performance requirements is in the weight range of 15 to 20 ounces per boot, the objective will have been attained.

d. Copper Foot and Climatic Chamber Studies

Six different prototype designs were fabricated. Copper foot data were obtained on four prototypes, and a pull-on type boot weighing 15½ ounces was worn in the climatic chambers at NLABS at -30°F for a period of two hours. The copper foot data were used to provide guidelines in determining thermal insulating properties of the selected materials constructed in a basic pull-on type design. The results indicated that the prototype boots provided approximately the same protection as the standard cold-wet boot for leg, heel, ankle and sole areas, but considerably less protection over the critical areas forward of the ankle.

The prototype boot weighing 15½ ounces (designated as Boot #5), representing the best results of experience gained from the materials and copper foot studies, was compared to a 38-ounce standard boot in the climatic chambers. This standard boot, the only one available at the time, had slightly less insulation than the boot being issued (See Appendix A).

The experimental prototype boots in a basic pull-on type conventional construction along with results of thermal insulation studies can be described as follows:

Experimental Boot #1 weighed approximately 16 ounces in a size 9R using the primary candidate materials. This boot was fabricated to develop basic fabricating techniques and to determine the formability characteristics of the materials and conformance to contours of the last. The boot was too small to fit on the sectional foot calorimeter (Copper Foot) for thermal insulation properties evaluation. To permit the use of the calorimeter in determining the thermal insulation properties of experimental boots, a new size 10 last was developed and used in the assembly of boots.

Experimental Boot #2 weighed 17.1 ounces and was fabricated using butt seams with reinforcing strips on the insulation seams. The inner liner was nylon fabric and the counter and toe cap was expanded ABS .070-inch thick.

Experimental Boot #3 weighed 16 ounces and was fabricated using lapped seams with skived edges, thereby eliminating the use of reinforcing strips on the insulation seams. The inner liner was Orlon fabric and the counter and toe cap was expanded ABS .145-inch thick.

The one-inch-thick outsole, midsole, insole combination of both experimental Boots #2 and #3 was molded in one piece from a closed-cell polyurethane possessing a density of 24.5 pounds per cubic foot.

The upper insulation in both boots was 1/8-inch-thick, closed-cell polyethylene possessing a density of 3.2 pounds per cubic foot.

The exterior coating on the boots, a polyether polyurethane compound, was applied by the spray method to .020 - .030-inch thick.

The Orlon fabric in Boot #3 had more body which resulted in good conformity to the boot last and better stitching than that of the previously used nylon fabric. Difficulties were encountered in preparing the butt seams for the upper insulation on Boot #2. The lap seams used for applying the upper insulation in Boot #3 increased the reliability and reduced the complexity of fabricating the seams.

Sectional insulating values for experimental Boots #2 and #3 were measured on the sectional foot calorimeter.[4] For comparison, values were determined for a standard black cold-wet insulated U.S. Army boot. The shape and location of the test zones on the copper foot are shown in Figure 1. Levels of insulation over the various calorimeter sections, in clo units, are given for each boot in Table II. These values indicate the contribution of the boundary air layer outside the boot plus that of the wool sock worn on the foot. No values are given for Sections 1-13 and 2-14 since these lower leg sections of the calorimeter were outside the boots.

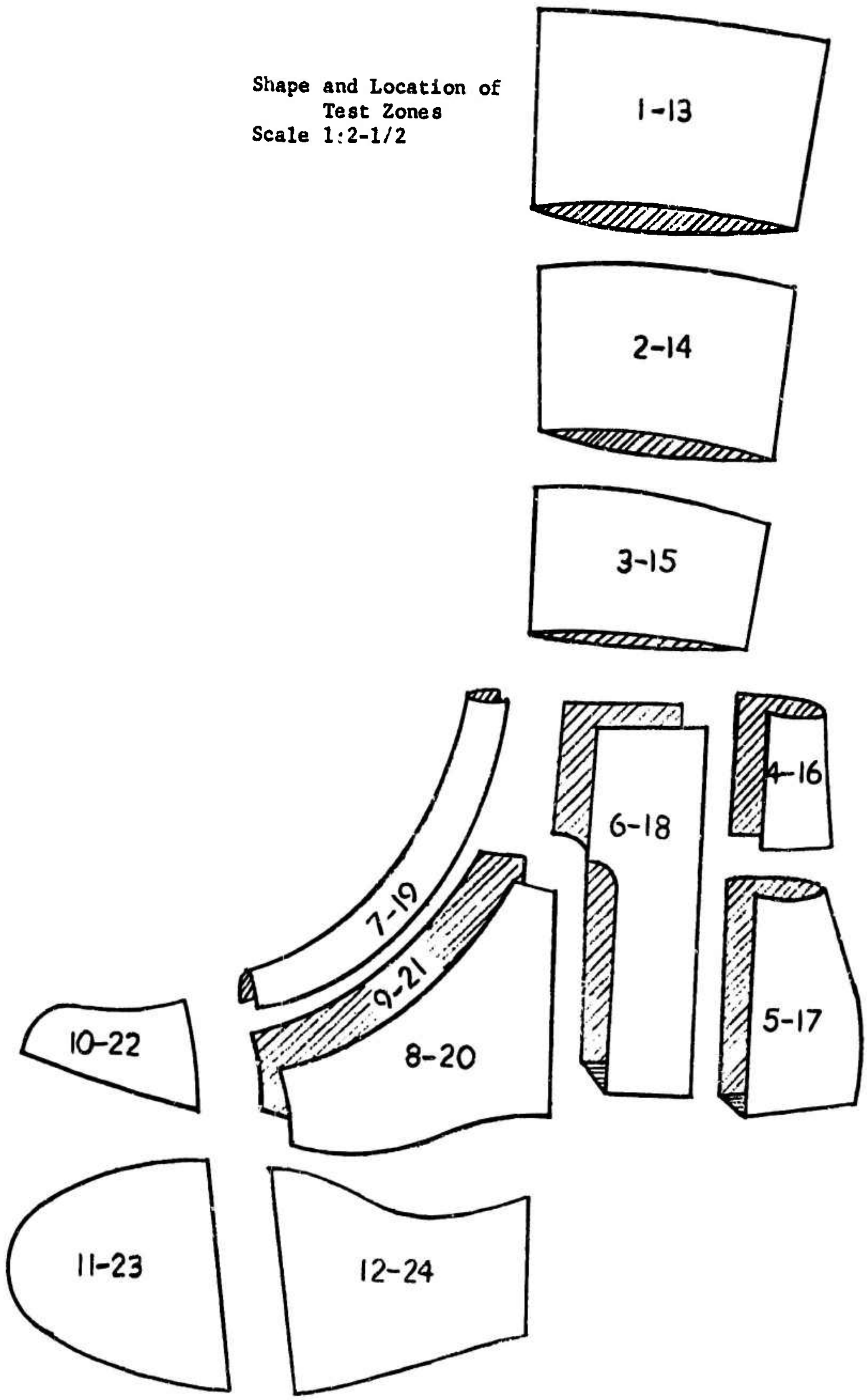

Figure 1. Copper Foot Test Zones

TABLE II

COPPER FOOT CALORIMETER DATA

Section	Standard Boot (10XW) (1,247 gms) (44 oz) Clo*	Boot #2 (490 gms) (17.1 oz) Clo	Boot #3 (454 gms) (16.0 oz) Clo
3-15	1.48	1.97	1.80
4-16	1.97	1.65	1.48
5-17	2.18	1.71	1.62
6-18	2.16	1.82	1.79
7-19	1.80	1.62	1.59
8-20	2.49	1.62	1.51
9-21	2.31	1.27	1.21
10-22	1.72	1.37	1.35
11-23	2.55	2.10	2.18
12-24	3.03	2.54	2.60
Overall (Sec 3-12)	2.00	1.72	1.66

* Clo: The amount of insulation necessary to maintain in comfort a sitting, resting subject in a normally ventilated room (air movement 20 ft/min) at a temperature of 70°F and a humidity of air which is less than 50 percent.

The standard boot values are for a size 10XW (extra wide) boot, which was the only size 10 boot available at the time of the study. The Calorimeter is sized to fit a size 10R (regular) boot and was a loose fit for the 10XW boot. For this reason, values obtained for the standard boot may be high.

Because readings from the test were recorded for the entire zone, pinholes or leakages through the insulation cannot be located precisely in each section by this test. The copper foot data showed that while the values for the two experimental boots were about the same, the values for the standard boot were much higher. Boot #2 had butt seams in the upper insulation while Boot #3 seams were skived and overlapped. The copper foot study did not differentiate between these two methods of construction. However, the experimental boots exhibited a major deficiency in the forward position of the foot area.

Based on the results obtained on Boots #2 and #3, the thickness of the upper insulation was doubled to approximately .250-inch on Boots #4, #5 and #6. Boot #4 weighed 16 ounces. In addition to doubling the thickness of the upper polyethylene insulation from 1/8-inch to 1/4-inch thick, the following changes from Boot #3 were made:

Figure 2. Component Parts for S'andard Black Insulated Boot

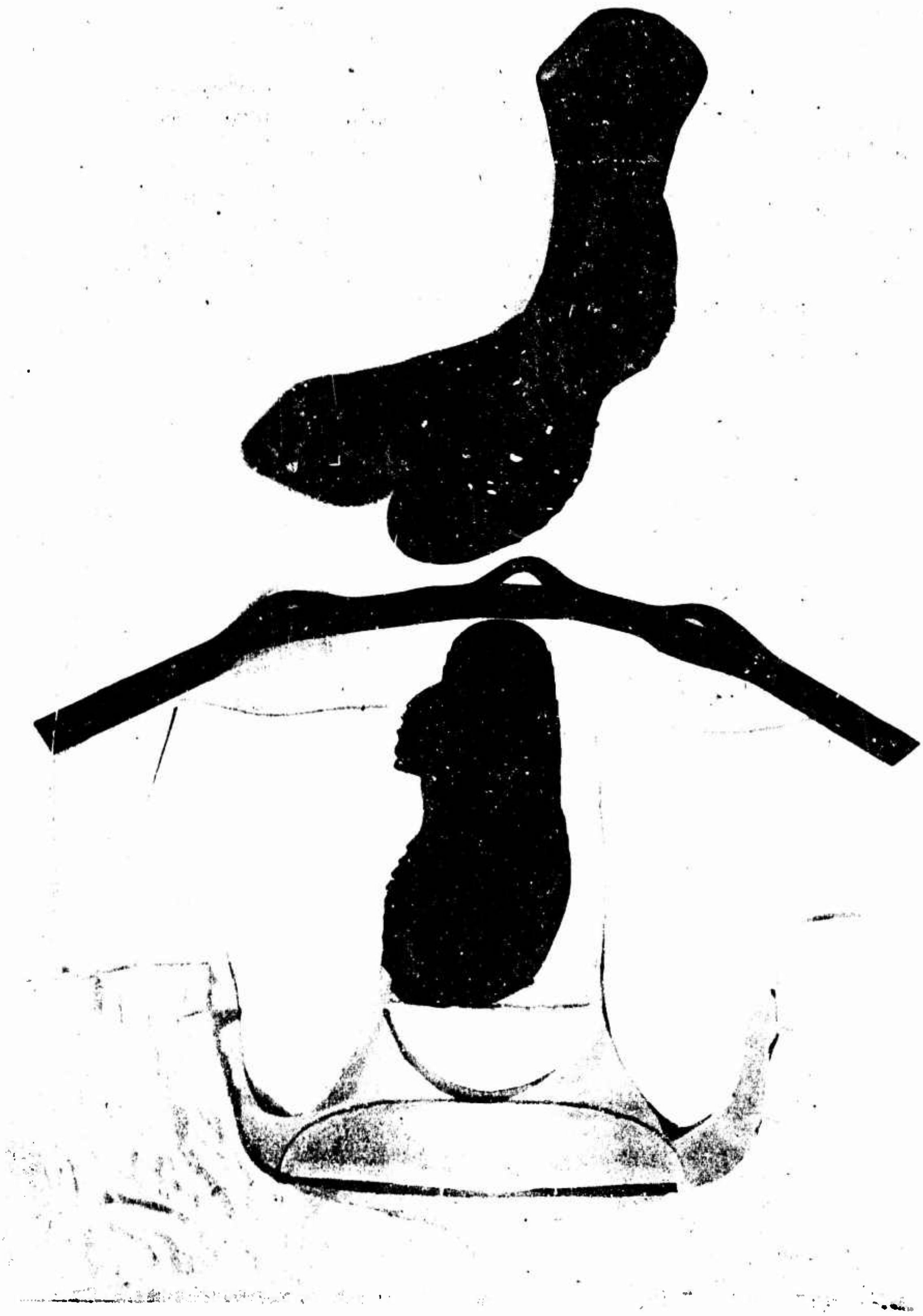

Figure 3. Component Parts for Prototype #5

The thickness of the polyurethane coating was reduced from .020 - .030 to .015 - .025-inch thick, and the polyurethane sole was reduced from approximately 1.0-inch thick to 0.75-inch thick.

Boot #5 weighed 15-1/2 ounces and was essentially equivalent to Boot #4. This boot was used in a walking test in the climatic chambers at -30°F. Table III details the lightweight materials while Figure 3 presents the component materials used to fabricate Boot #5. When the components presented in Figure 3 are compared with the components of the standard black insulated boot (Figure 2), the reduction in the number of components and in the finished weight becomes significant.

TABLE III

DESCRIPTION OF EXPERIMENTAL LIGHTWEIGHT MATERIALS
ASSEMBLED IN BOOT FORM (BOOT #5)

Nomenclature	Material	Density (lbs/cu/ft)	Thickness (inches)
Lining fabric	100% Orlon	---	---
Upper insulation	Closed-cell polyethylene	3.0 - 3.5	0.253
Toe cap and counter	Rigid, cellular acrylonitrile/butadiene styrene (ABS)	13.0	0.145
Insole-Midsole-Outsole	Closed-cell polyurethane	25 - 27	0.725
Reinforcement strips	Polyurethane	---	---
Shank support	Stainless steel	---	---
Adhesive	Neoprene base	---	---
Exterior coating	Polyether polyurethane	---	0.20

Boot #6 was fabricated because Boot #4 was too rigid due to increased thickness of insulation. Boot #6 weighed 14.9 ounces. The principal feature of this boot was the use of two layers of 1/8-inch-thick poly-ethylene insulation instead of one layer of 1/4-inch-thick insulation. To allow for greater flexibility, the two layers were adhered together at the outer edges only. A one-piece, knit weave, polypropylene, 3.75 - ounce/square yard inner liner was substituted for the Orlon liner used in

Boots #4 and #5, and the design of the liner was changed to eliminate the back seam, thereby reducing the possibility of seam failure due to abrasion when donning and doffing. It was also anticipated that the use of polypropylene sock lining would increase slip and contribute to ease of donning and doffing. The remainder of the boot was the same as those of Boots #4 and #5.

Sectional insulating values for experimental Boots #4 and #6 were measured on the calorimeter (Table IV). Although the thickness of the polyethylene insulation in Boots #4 and #6 was approximately double that of Boot #3, the slight increase in clo value of these boots was not significant and the insulation properties were not considered adequate.

A comparison of the results for prototype Boots #4 and #6 shows that the boots have approximately equivalent insulation values. Although the construction and method of use of the insulating materials within the two boots was different, the thickness in insulation over any given foot section of Boot #6 was equivalent to that of Boot #4.

With their present configurations, Boots #4 and #6 provide approximately the same protection as the standard cold-wet boot for leg, heel, ankle and sole areas, but considerably less protection over the critical forward areas, sections 7 to 10 on the calorimeter. It was anticipated that this deficiency would be corrected by increasing the thickness of insulation forward of the ankle region.

TABLE IV

COPPER FOOT CALORIMETER DATA

Foot Section	Standard Boot 10XW 44 oz. (Clo)	Boot #4 16.0 oz. (Clo)	Boot #6 14.9 oz. (Clo)
3 - 15	1.61	1.35	1.79
4 - 16	1.87	1.73	1.54
5 - 17	1.92	1.82	1.89
6 - 18	2.19	1.94	1.73
7 - 19	1.98	1.73	1.50
8 - 20	2.71	1.86	1.88
9 - 21	2.55	1.63	1.69
10 - 22	1.88	1.49	1.54
11 - 23	2.81	2.02	2.02
12 - 24	3.43	2.16	2.66
Overall (Sec 3-12)	2.10	1.71	1.76

The lower clo values obtained in the sole sections of Boots #4 and #6 resulted from the reduction in the sole thickness by approximately 1/4-inch. The thickness of the sole in Boot #3 was considered excessive because of undue stiffness and was reduced to provide better design and construction features. This reduction in thickness was not expected to affect the protective capability of the sole. The lower clo value in Boot #4 from that of Boot #6, obtained in Section 3-15, cannot be explained.

Boot #5, which is essentially equivalent in insulating properties to Boots #4 and #6, was worn in the NLABS climatic chambers during an actual human evaluation test. The results of this test demonstrated that the experimental materials selected, when assembled in the form of a boot which weighs only 15.5 ounces, may satisfy the basic functional objectives of a lightweight, insulated, impermeable boot (See Appendix A).

e. Program Review

The materials research studies, prototype fabrication and evaluation were reviewed at this time to determine the progress made and which work should be continued. It was determined that materials research and design development had progressed sufficiently to demonstrate that the materials selected could be formed, shaped and assembled into a boot.

The preliminary performance studies (copper foot and cold chamber) indicated that the required thermal insulation properties for a lightweight insulated boot might be achieved. However, such features as durability, service life, comfort during prolonged wear, and general response to design had yet to be resolved.

Based upon the results, it was determined that work should continue toward the development of improved materials and processing methods for producing candidate cellular compounds for major boot components, and that improved design and fabrication concepts for producing lightweight insulated footwear for initial evaluation should be investigated.

4. Phase II - Materials, Design, Testing and Fabrication of Prototype Footwear

a. Approach

Studies were conducted on the development of the optimum compounds and processing techniques for producing materials for boot components. The materials for the compounding and processing studies were selected from the promising materials uncovered in the Phase I program. These included expanded polyethylene, polyurethane, neoprene and ethylene propylene terpolymers.

During the engineering design and fabrication studies, attempts were made to combine sections of footwear so that the resulting product would have as few components as practical.

In addition to the use of conventional assembly methods of fabricating footwear, consideration was also given to the development of techniques for producing an integrally cast, expanded polyurethane insulated boot. The objective was the completion of 50 pairs of each of three prototypes of lightweight insulated footwear chosen through the investigation and selection of improved materials and processing methods and new design and fabrication concepts.

b. Materials Discussion

Outsole/Midsole/Insole

The previous compounds developed for the outsole/midsole/insole from water-expanded polyurethane exhibited rapid cracking failures upon flexing. Formulation studies, including combinations of polymers, did not produce the required improvement in flex life and abrasion resistance.

Although it was recognized that an expanded neoprene sole would not be as suitable for production as would polyurethane because of the required complex fabricating techniques, a method was developed to produce a sole. This neoprene outsole/midsole/insole combination, similar in appearance to the sole made from the expanded liquid polyurethane system, was developed so that an alternate soling material would be available if all of the desired properties could not be built into the polyurethane soling. Studies to overcome the deficiencies noted in the water-expanded polyurethane sole resulted in the development of a new technique using methylene chloride for expanding the polyurethane sole.(5) By accurate control of ingredients and mold temperatures, a product was made with a skin already formed on the outside and a density gradient within the finished material. Continuing studies with this system resulted in the development of a one-piece outsole/midsole/insole combination with excellent physical properties. The outer skin increases resistance of the sole to abrasion and flex crack wear. Although the properties of this skin approach the excellent wear and physical characteristics of the solid polyurethane, the skin density will never equal that of the solid material since some degree of blowing will always occur. This development was completed in time to allow for the use of this specific sole on all of the footwear produced on a semi-production basis.

c. Upper Insulation

Expanded Polyethylene for Upper Insulation

Studies were conducted to improve the compression set properties over those of the expanded polyethylene material used for the prototypes in Phase I. The additional compounding studies produced an expanded material with improved compression set properties and low temperature flexibility.

Expanded Polyurethane for Upper Insulation

The advantages of a closed-cell, low density polyurethane material over those of the closed-cell polyethylene are a more flexible material, less complexity in handling and greater compatibility with other materials under consideration for fabrication of items. Extensive studies resulted, for the first time, in the production of a seven-pound-per-cubic-foot, true closed-cell polyurethane from chemically-cured millable polyurethane elastomer.

Expanded Ethylene Propylene Terpolymers for Upper Insulation

Since ethylene propylene terpolymers possess excellent low temperature properties, compounding studies were conducted to develop materials for use as upper insulation. The compounding studies resulted in materials that were adequate for testing but their densities were too high for consideration as upper insulation. In addition, studies would have been required to develop suitable adhesives; therefore, this material was not given further consideration.

d. Design and Fabrication Studies

Design and fabrication studies were conducted concurrently with the materials studies. The results achieved in Phase I indicated that the basic pull-on boot design should be the starting point to achieve the weight objective and keep the number of component parts to a minimum. This pull-on design approach introduced the problem of anchoring the boot firmly enough to the foot to allow comfort while walking. Because of the great range in foot shapes that must be fitted, sufficient room in the leg-ankle area for ease of donning and doffing must be considered. A proper fit is difficult to achieve with the relatively few foot sizes currently available. It is recognized that boots must be comfortable and fit properly, otherwise the efficiency of the wearer is affected. Therefore, studies were conducted of closure types and areas for closure locations, which would allow ease of donning and doffing and permit firm anchoring of the boot to the foot.

During the design and fabrication studies, prototype boots were produced and evaluated. Based upon detailed laboratory studies, limited wear tests, and insulating values determined on the sectional foot calorimeter, design and fabrication techniques were developed and modified to produce the optimum footwear.

Fabrication studies employed two different approaches:

(1) Boots were constructed by conventional fabrication techniques using the minimum possible number of components fabricated from materials carefully selected on the basis of performance requirements for various boot areas. Hand assembly was used for this non-vulcanized construction.

(2) An unconventional (at least for footwear) integral casting technique was developed. This process resulted in the production of an expanded polyurethane boot construction foamed-in-place with a minimum number of components.

e. Prototype Boots Produced by Conventional Fabricating Techniques

The major deficiency of the prototype boots fabricated in Phase I was their low insulative values in the toe and vamp area. To overcome this deficiency, prototype Boot #7 in a pull-on type design weighing 15.5 ounces was fabricated (Table V).

TABLE V

DESCRIPTION OF EXPERIMENTAL LIGHTWEIGHT MATERIALS ASSEMBLED IN BOOT FORM (BOOT #7)

Nomenclature	Material	Density (lbs/cu/ft)	Thickness (inches)
Lining fabric	100% polypropylene knit	---	---
Upper insulation	Closed-cell polyethylene	3.0 - 3.5	.25
Toe cap & counter expanded	Rigid, cellular acrylonitrile/butadiene/styrene (ABS)	13.0	0.145
Insole-midsole-outsole	Closed-cell polyurethane	25 - 27	0.725
Reinforcement strips	Polyurethane	---	.015
Shank support	Stainless steel	---	
Adhesive	Neoprene base	---	
Exterior coating	Polyether polyurethane spray coating	---	.015

In addition to the materials outlined in Table V, an additional piece of closed-cell polyethylene, approximately 0.25-inch thick, was placed on the instep and around to the shank area, covering the entire forepart of the foot. The entire boot assembly was then sprayed with a polyether-polyurethane coating approximately .015-inch thick to provide an abrasion-resistant exterior.

Prototype Boot #9 weighing 18.75 ounces was assembled. This boot was similar in construction to Boot #7 except that a closed-cell polyurethane was substituted for closed-cell polyethylene in the upper insulation. This closed-cell polyurethane was the material developed from a chemically-cured millable elastomer. The overall gauge of this material was approximately .25-inch thick and the density was approximately six pounds per cubic foot. The additional piece of insulation placed in the critical areas forward of the ankle averaged .20-inch thick.

Table VI presents the sectional foot calorimeter data obtained on the two described prototype boots assembled with the optimum materials and using the final construction techniques.

TABLE VI

COPPER FOOT CALORIMETER DATA

Foot Section	Standard Cold-Wet Boot* 48 ounces (Clo)	Polyethylene Insulated Boot #7 15.5 ounces (Clo)	Polyurethane Insulated Boot #9 18.75 ounces (Clo)
3-15	1.62	1.82	1.32
4-16	1.81	1.96	1.49
5-17	2.00	1.98	1.74
6-18	2.06	2.01	1.95
7-19	1.52	1.88	1.71
8-20	2.76	2.50	2.27
9-21	2.13	1.81	2.13
10-22	1.68	2.02	1.86
11-23	2.31	1.80	1.96
12-24	2.82	2.32	2.31
Overall (Sec. 3-12)	1.93	1.98	1.77

* Standard boot labeled "Contract #1-1188-63-ENE US 8-62" - weight marked 48 ounces

NOTE: Boot #7 is identical to Boot #8 but is for a right foot while Boot #8 is for a left foot.

A comparison of the values for prototype Boot #7 insulated with expanded polyethylene (15.5 ounce weight) with those for the standard boot shows that this prototype, when new, has equal or higher insulation values than the standard boot except in the sidewalls forward of the ankle (sections 8 and 9) and sole (sections 11 and 12), (Figure 1). The insulation over the toe area is greater than that of the standard boot, but it is not known whether the lower insulation under the toes (section 11) in the prototype boot will tend to offset the higher insulation obtained in the toe cap.

The polyethylene insulated prototype #7 was informally worn in the climatic chambers at -30°F in a two-hour, slow-walking test and a 30-minute sitting test. The 15.5-ounce experimental boot was worn on the right foot and the standard boot was worn on the left. Thermocouples were attached to each foot as follows:

1. big toe
2. little toe
3. instep
4. ankle

Table VII presents the results of the -30°F climatic chamber study.

TABLE VII

TIME-TEMPERATURE RELATIONSHIP

	Polyethylene Experimental Boot 15-1/2 oz (Boot #7)			Standard Boot 48 oz		
	60 min	120 min	150 min*	60 min	120 min	150 min*
1. Outside big toe	83.5°F	73°F	59.5°F	81.0°F	70.0°F	54.0°F
2. Outside little toe	89.5	83.0	71.0	81.0	62.1	53.5
3. Instep	87.0	83.5	74.5	87.0	83.5	72.0
4. Ankle	86.0	82.5	78.0	85.0	80.0	72.0

* 120 minutes slow walking, remaining 30 minutes sitting.

This informal study substantiated the copper foot data in Table VI and again indicated that the 15.5-ounce experimental polyethylene insulated boot, when new, exhibits approximately equal insulating properties to those of the standard boot.

With reference to the polyurethane insulated Boot #9, the sectional and overall insulating values were lower than for the polyethylene insu lated Boot #7.

Initial material studies in the laboratory indicated that closed-cell polyurethane should have higher insulating properties per unit of thickness at a given density than the polyethylene insulation in Boot #7. The lower insulating values obtained by the copper foot calorimeter may be partly attributed to the higher density (6.0 lbs/cu/ft) of the polyurethane as compared with that of the polyethylene (3.0 lbs/cu/ft). In addition, the expanded polyurethane is much more flexible than the expanded polyethylene; therefore, the possibility exists that tension during the lasting operation may have depressed and reduced the thickness of the insulating expanded polyurethane material.

f. Prototype Boots Produced by the Casting Technique

The second approach embodied a radical change in fabrication of insulated boots. This concept involved the development of a method to integrally cast or expand in place a boot of unified construction. It also required a compound that would be a free-flowing, low-viscosity, quick-setting, expandable composition with a fairly long pot life after mixing. The compound should have the ability to produce a low-density expanded material with a high content of closed cells that would provide good insulating values and still be flexible.

In the first attempt to cast insulated boots of unified construction, the outsole was produced from a pre-molded, water-blown, closed-cell polyurethane. The upper polyurethane insulation was integrally cast to the pre-molded outsole. The upper polyurethane insulation was a nitrogen expanded open-cell system. The 10-mil-thick polyether-polyurethane outer skin was applied by spray-coating. This method was used to determine the feasibility of producing a boot by the casting process.

Results of sectional calorimeter copper foot studies (Table VIII) showed that the initial attempts to cast a unified boot (Boot 1C-1) resulted in markedly reduced insulating values when compared with those for the conventionally constructed prototype #7. A cut section of the boot exhibited voids, indicating poor flow of the compound into the mold intricacies. A contributing factor to poor compound flow was that the epoxy mold was crudely made and the heat transfer through the mold was inadequate. However, this initial effort indicated that it might be feasible to produce insulated boots by this approach.

New mold construction and design studies, including extensive studies to improve compound properties and casting techniques, resulted in the successful production of Boot #IC-3 by the newly developed integral casting technique. The polyurethane for the upper insulation and the sole was foamed in place (using nitrogen as the expanding agent) over a textured nylon sock lining.

The copper foot data (Table VIII) on Boot #IC-3 indicate that this boot, when new, provides essentially the same sectional insulating values as the standard cold-wet (black) boot.

TABLE VIII

COPPER FOOT CALORIMETER DATA

Foot Section	Standard Cold-Wet Boot 48 oz (Clo)	Polyethylene Insulated Boot #7, 15.5 oz (Clo)	Integrally Cast Boot IC-1 18.6 oz (Clo)	Integrally Cast Boot IC-3 19.1 oz (Clo)
3-15	1.62	1.82	1.63	1.64
4-16	1.81	1.96	1.33	1.72
5-17	2.00	1.98	1.51	2.05
6-18	2.06	2.01	2.06	2.06
7-19	1.52	1.88	1.42	1.89
8-20	2.76	2.50	1.63	2.67
9-21	2.13	1.81	1.81	2.24
10-22	1.68	2.02	1.25	1.85
11-23	2.31	1.80	2.08	2.31
12-24	2.82	2.32	2.25	2.61
Overall (Sec 3-12)	1.93	1.98	1.63	2.01

g. Closure Design Study

During the engineering design phase of the lightweight footwear prototypes constructed by conventional methods, evaluation of various types of closures was conducted along with the basic pull-on type concept. The efforts expended during the closure design study were necessarily guided by the major objectives of light weight, low water absorption, and adequate thermal insulation.

Slide fastener closures on the back and side of the boot, snap steel closures, and an adjustable buckle and strap attached to the top portion of the boot were evaluated.

A snap steel-type closure was designed in an attempt to anchor the boot firmly enough to the foot so that all possibilities of slippage and shucking at the heel would be eliminated for foot comfort while walking, and to provide ample room in the leg ankle area for ease of donning and doffing.

Using the conventionally assembled boot insulated with polyurethane, a fold-over snap-steel-type closure was fabricated on the side of the boot. This steel closure was equipped with a swivel on the bottom which allowed the closure to open while donning the boot and to then snap close by itself. The fold-over area required to form the pocket of the snap-steel closure was insulated. The concept was that the snap-steel closure would be kept closed through the action of the trouser leg drawstring when the trouser legs were pulled down over the boots.

The finished boot weighed approximately 25.5 ounces. The increase in weight is attributable to the additional insulation required for the fold-over area as well as the added weight of the snap-steel closure. Although the finished weight of 25.5 ounces per boot was considered excessive for lightweight insulated footwear, copper foot studies were conducted to determine if there would be any insulation loss in the closure area. A comparison is given in Table IX of the insulating value of the boot with the snap steel closure versus the pull-on-type boot using the same polyurethane insulating materials and similar construction techniques except for the closure area. This boot weighed 18.75 ounces compared with the 25.5 ounces of the boot with the closure. The copper foot results show that protection was not appreciably altered by the addition of the closure on the side of the boot. The values for section 6, the boot zone in which the closure appears, were identical for both boots.

TABLE IX

COPPER FOOT CALORIMETER DATA

Foot Sections	Polyurethane Pull-On Boot (without closure) 18.75 ounces (Clo)	Polyurethane Boot (with closure) 25.5 ounces (Clo)
3-15	1.32	1.24
4-16	1.49	1.54
5-17	1.74	1.99
6-18	1.95	1.95
7-19	1.71	1.83
8-20	2.27	2.46
9-21	2.13	2.07
10-22	1.86	1.94
11-23	1.96	2.11
12-24	2.31	2.26
Overall (Sec 3-12)	1.77	1.82

Upon further consideration it was also determined that it would not be practical to place reliance upon the drawstring of the trousers to maintain the snap closure in the closed position continuously. Zipper closures in various areas of the boot, such as the back or over the ankle, were given serious consideration. A prototype boot was fabricated with a zipper closure; however, the boot materials were not flexible enough to allow adequate take-up when the zipper was pulled closed. Complex fabricating techniques were required to insure reliability of insulation properties. In addition, the possibility of snow and ice clogging the teeth reduced the reliability of the zipper.

The results of these studies indicated that the best approach for provision of a closure, if required to anchor the boot to the heel, was to remain with the basic pull-on type concept and add a simple take-up strap with a roller-type buckle on the upper portion of the boot which would pull the boot up tight around the calf of the leg.

Studies conducted to determine the effectiveness of the take-up strap indicated that while the strap will secure the boot to the leg, it will not completely eliminate slippage or shucking at the heel. However, the degree of slippage remaining in the heel area was not considered critical.

h. <u>Prototype Selection for Production of Items</u>

Based upon the results of the process studies, design and fabrication studies, evaluation of prototype boots on the sectional copper foot calorimeter and limited wear tests, three prototypes with two variables each were selected to be produced on a pilot production line geared to a limited commercial production basis.

Production techniques were developed and personnel were [illegible]en special training sessions prior to the start of production.

The prototype boots produced in size 9R were as follows:

(1) Integrally cast all-polyurethane boots with shanks

(2) Integrally cast all-polyurethane boots without shanks

(3) Polyurethane insulated boots with take-up strap closure

(4) Polyurethane insulated boots without take-up strap closure

(5) Polyethylene insulated boots with take-up strap closure

(6) Polyethylene insulated boots without take-up strap closure

Boots #3 through #6 all had shanks and were produced by conventional fabrication methods.

The variations presented were required because not enough data were available to determine whether the shank reinforcement would be required in the integrally cast boots and whether the effectiveness of the take-up strap would be significant enough to be acceptable as part of a finished item.

The finished boots are described as follows:

Prototype 1

This boot is made of all-polyurethane from a two-component, integrally cast system of pull-on style approximately 11 inches high with a steel shank reinforcement in the sole. The 3/4-inch-thick outsole is produced in a herringbone tread design from a methylene chloride expanded polyether-polyurethane liquid prepolymer with a solid outer skin and a density gradient resulting in an average core density of 25 pounds per cubic foot. The insulating material as it is formed in the upper is a five-pound-per-cubic-foot polyurethane (approximately 90% closed-cell). The inner lining or sock lining of the boot is a film of polyether-polyurethane tightly adhering to the insulating material to provide good slip for donning and doffing. To provide a durable abrasion-resistant exterior, the boot has a sprayed-on outside skin of polyether-polyurethane. In size 9R, the boot weighs 18 to 20 ounces per boot, or about half the weight of the present Standard Insulated Boot.

Prototype 2

This boot is identical to Prototype 1 except that it was produced without a shank.

Prototype 3

This boot is made of polyurethane, conventionally fabricated (lay-up) boot of pullover style approximately 11 inches high and with steel shank reinforcement in the sole. The approximately 6/10-inch-thick outsole is produced in a herringbone tread design from a methylene chloride expanded polyether-polyurethane liquid prepolymer with a solid outer skin and a density gradient resulting in an average core density of 21-22 pounds per cubic foot. The insulating material in the upper is a closed-cell, 6-7 pound-per-cubic-foot-density polyurethane produced from a chemically blown millable gum. The polyurethane insulating material in the upper extends to a height of 5-1/2 inches (inside dimension), leaving a 4-1/2-inch-high flexible cuff at the boot top to which a take-up strap and roller buckle are riveted. The inner lining or sock lining is a 3-ounce-per-square-yard nylon jersey which provides good slip characteristics for donning and doffing. To provide a durable abrasion-resistant exterior, the boot has a sprayed-on outside skin of polyether-polyurethane. In size 9R, the boot weighs 17 to 19 ounces per boot.

Prototype 4

This boot is identical to Prototype 3 except that there is no take-up strap.

Prototype 5

This boot is also identical to Prototype 3 except that the insulating material in the upper is a closed-cell 2.5 to 3.0 pound-per-cubic-foot-density polyethylene. In size 9R, it weighs 13 to 16 ounces per boot.

Prototype 6

Identical to Prototype 5 except that there is no take-up strap.

i. Low Temperature Evaluation of Selected Prototype Boots

The three basic types of lightweight insulated boots and the standard black insulated boot were cold-soaked in the cold box at -30°F for six hours. There was a significant stiffening of the three lightweight boots. Without removing the lightweight boots from the cold box, the boots were hand-flexed and struck with a hammer with the following results:

(1) It was impossible to bend the outsoles of any of the boots by hand.

(2) The integrally cast boot was more flexible than the other two conventionally fabricated types.

(3) There was no visual shattering or break in any part of the boots.

(4) There was no marring of the outer skin.

One lightweight boot of each type was removed from the cold box and immediately donned without difficulty; however, the boots appeared to fit a little more snugly than when donned at room temperature, possibly because of the reduced flexibility and give caused by cold-soaking.

The current standard (black) wet-cold insulated boot showed no apparent change in flexibility after being cold-soaked for six hours at -30°F.

One integrally cast polyurethane boot was cold-soaked in the cold box at -65°F for six hours. The boot became stiff and rigid to the point where there was no give to the materials. This indicated that at this temperature the footwear would be extremely difficult to don. Without removing it from the cold box, the boot was struck with a hammer in all of the critical areas in an attempt to crack or shatter the materials at -65°F. When the boot was returned to room temperature, a visual examination showed no cracks or shattering of the materials.

Based upon these results, a limited chamber study (Appendix B) was conducted to determine the effect of low temperature on materials, the flexibility of construction, donning of footwear, and walking ability after footwear had been cold-soaked at -20°F. The results of this study indicated that new boots cold-soaked at -20°F for six hours can be donned and flexed at low temperature, walked in without impairing walking ability, and suffer no visual effects on materials and construction.

j. <u>Hydrolysis Resistance of the Integrally Cast All-Polyurethane Boot</u>

Hydrolysis resistance was conducted on the integrally cast all-polyurethane boot because it is known that some polyurethanes have shown poor resistance to humid ageing. One boot was exposed in the NLABS tropical chamber for 160 days at a temperature of 85-86°F and a relative humidity of 95%. This chamber closely simulates tropical conditions and any material that is susceptible to microbiological attack will deteriorate. The length of time required to initiate microbiological attack is dependent upon the material being evaluated.

The weight of the all-polyurethane boot prior to test was 502.7 grams. At the end of the 160 days the boot was removed from the tropical chamber, the visible moisture was blotted dry and the boot immediately weighed. The weight of the boot increased by 14.2 grams (total boot weight 516.9 grams) for an overall increase in weight of 2.8%. The desired maximum allowable water absorption increase by weight for impermeable insulated boots is 5%. The boot was allowed to remain at room temperature for 24 hours and then reweighed. The overall weight was 505 grams or an increase of only 2.3 grams over the original weight. This remaining increase in weight was considered negligible from the standpoint of water absorption. Therefore, the increase in weight of 14.2 grams recorded immediately upon removal from the chamber may be attributed to residual moisture remaining on the outer surfaces of the boot and not moisture absorbed into the boot materials. This indicated that during the service life of the boot there should be no moisture pick-up of the polyurethane insulation from foot perspiration and from water spillage over the tops of the boots. The boot materials may be considered as resistant to hydrolysis.

Although resistance to microbiological attack is not an important consideration for low temperature service, the boot was inspected visually at regular intervals during the course of the test. Upon completion of the test, there were no signs of microbiological degradation.

k. Arctic Research Test

A research test of the prototype lightweight insulated boots was conducted in Alaska under Arctic winter conditions by the U. S. Army Arctic Test Center. The prototypes selected for test were:

Prototype A

Integrally cast all-polyurethane boot with shank reinforcement.

Prototype B

Boots with polyurethane insulated upper, shank reinforcement and take-up strap.

Prototype C

Boots with polyethylene insulated upper, shank reinforcement and no take-up strap.

The prototype boots were tested by the Infantry, Airborne and Individual Equipment Test Division of the U. S. Army Arctic Test Center during the period 1 March through 21 May 1968.[6] The items were tested for suitability, compatibility, durability, human factors and safety, and maintainability in ambient temperature ranges of 47°F to -25°F. It was concluded that:

(1) The insulation qualities of the test items are satisfactory for use under Arctic winter conditions.

(2) Traction provided by the sole is not adequate.

(3) The outer covering is not durable or heat-resistant.

(4) The socklining is not secured properly in Prototypes B and C.

(5) The test items are reliable and maintenance-free except for routine cleaning.

(6) The test items in their present state are not suitable for U. S. Army use under Arctic winter conditions.

The results of this limited research Arctic test indicate that it may be feasible to provide thermal insulating properties equivalent to those obtained in the standard (black) cold-wet insulated boot, with a significant reduction in weight.

5. Summary

The results of materials research studies and design development demonstrated that the materials selected could be assembled or formed into a boot.

Limited copper foot sectional calorimeter data and preliminary performance studies indicated that the desired thermal insulation properties for a lightweight insulated boot may be achieved.

Maximum weight reduction, while retaining the required insulating properties, may be achieved through the use of expanded materials in a boot of a basic pull-on design.

Lightweight insulated boots in the weight range of 15-20 ounces per boot have been fabricated.

A reduction to practice of the concept of integrally cast expanded polyurethane footwear was achieved and shown to be feasible on a semi-production basis.

Low temperature tests at -30°F showed significant stiffening of finished boots. There appeared to be no significant effect on the functional aspects, such as donning and walking ability of the cold-soaked, stiffened boots.

The integrally cast expanded polyurethane prototype footwear (18-20 ounces per boot), when new, provides equivalent insulation to the standard (black 40-43 ounces per boot) cold-wet boot, but may have reduced durability and service life.

6. Conclusions

The results of the preliminary studies conducted on what may be considered as the first generation of lightweight insulated footwear indicate that the integrally cast boot in a pull-on type construction offers the greatest potential of meeting the requirements of a lightweight (15-20 ounce per boot), impermeable water absorption (maximum weight gain 5%), insulated (for service down to -20°F) boot for periods of up to two hours of inactivity. The integrally cast technique permits a reduction in the number of parts required, as well as the elimination of seams, adhesives, and complex fabricating techniques that could result in weak areas or failure points in boots assembled by conventional fabricating techniques.

Boots in a pull-on type construction produced by the integrally cast method should result in boots that are more reliable from the standpoint of retaining insulating properties, less complex to produce, lighter in weight and lower in cost. In addition, the boots produced by this technique may be superior in areas of fit and flexibility than the conventionally fabricated boots in a pull-on type construction.

7. Future Work

Future work will be related directly to optimization of the physical properties of selected compounds, and to final development of construction and design of a pull-on type integrally cast boot. Consideration will also be given to the concept of a one-step molding operation to eliminate multiple castings, thereby increasing the reliability of the finished boot. Such features as fit, comfort during prolonged use, styling, wear and general response to design will be given special attention.

8. References

1. L'Hollier, L. H., and Alice Park, Sealed Insulated Military Boots, U. S. Army Natick Laboratories TR 68-32-CM, November 1967.

2. Pooley, R. W., L. E. Fisher, and A. D. Shaw, Lightweight Insulated Footwear, U. S. Rubber Company, Contract No. DA19-129-AMC-690(N), U. S. Army Natick Laboratories TR 67-23-CM, September 1966.

3. Pooley, R. W., A. D. Shaw, and C. S. Rohs, Lightweight Insulated Footwear, Uniroyal, Incorporated, Contract No. DA19-129-AMC-959(N), U. S. Army Natick Laboratories TR 69-16-CM, July 1968.

4. Research Study - Areas of Effective Insulation in Cold Climate Footwear and Development of the Sectionalized Foot Calorimeter, Clothing Branch Series Report No. 16, QMR&E Command, Natick, Mass. (1960)

5. Bianca, D. and R. E. Knox, Elastomer Chemicals Department, E. I. duPont deNemours & Company, Inc., Wilmington, Delaware: New Method for Producing Microcellular Polyether Urethane Rubber, presented before Division of Rubber Chemistry, American Chemical Society, Miami Beach, May 1965.

6. Hicks, A. S. Jr., Captain, U. S. Army Arctic Test Center, Alaska. Research Test of Lightweight Insulated Boot Under Arctic Conditions, 31 May 1968, RDT&E Project No. 1J624101D504, USATECOM Project No. 8-7-6007-01.

APPENDIX A

LABORATORY REPORT CF #19 20 June 1966

Preliminary Climatic Chamber Evaluation of Experimental Lightweight Insulated Boot Materials*

BY: JOSEPH E. ASSAF

Background

Under Project title, "Individual Combat Protective Clothing and Equipment, Exploratory Development," materials research studies are being conducted to develop new lightweight materials to be used as components or groups of components in fabricating lightweight insulated footwear.

There are presently two standard insulated boots in the system. They are described as follows:

1. Boot, Insulated, Cold Weather, Rubber (Black) for Wet Cold Use. These boots have been designed to protect feet where the mean monthly temperatures range between 14°F and 68°F. The boot should not be worn when temperatures fall below -20°F.

2. Boot, Insulated, Cold Weather, Rubber (White) for Cold Dry Use. These boots have been designed to protect under sub-zero conditions and should be worn when ambient temperatures of -20°F or below may occur.

Concurrent with the study reported, properties other than insulation are being investigated. The results will be the subject of future reports.

Test Procedure

Based upon data obtained to date from materials research studies being conducted with U. S. Rubber Company under Contract No. DA19-129-AMC-690(N), candidate materials in a general boot form were assembled by basic fabrication techniques in a pull-on type design. This experimental boot was used to determine the insulating properties of the materials in combination with each other. The finished assembly of these experimental materials weighed 15.5 ounces as shown in Figure 1.

* The cooperation and assistance of Pfc James Mailman, CRL, Coordination Office in attaching the thermocouples and in preparing for the test is gratefully acknowledged.

C O P Y

Figure 1. Assembly of materials in general boot form

The only "standard" boot available at the time of test had a 1/4-inch felt (instead of the 3/8-inch of the regular standard) for the insoles and 11.5-ounce fleece (instead of the 19-ounce for the regular standard) for the upper insulation. This boot weighed 38 ounces.

The author, acting as test subject, wore the 15.5-ounce experimental boot on the right foot and the black 38-ounce standard insulated boot on the left foot for two hours in the NLABS climatic research test chamber at -30°F. In order to study the insulating properties of the materials and determine the feasibility of providing lighter weight insulated boots without significantly decreasing the effectiveness of the insulating value over that of the current standard black insulated boot, thermocouples were attached to each foot as follows:

1. Big toe
2. Little toe
3. Instep
4. Ankle

Figure 2 illustrates the location of each thermocouple.

A single standard cushion-sole wool sock was worn on each foot and the uniform was that for standard cold weather Army use.

Evaluation of Climatic Chamber Test Data

Figures 3, 4, 5, and 6 present a comparison of the rate of change in temperature of the various parts of the foot in the control and experimental boot over the two-hour period at -30°F.

Under the conditions of this limited study, the data show that, when new, the experimental boot is equal in insulating properties to the standard test boot.

Figure 3 compares the temperature change in the little toe area. The data show that the standard boot exhibits slightly better insulating properties in this area. However, the results toward the end of the two-hour test period indicate that the two boots can be considered equivalent in insulating properties.

The 26-minute period (between the 40 and 66-minute periods in the test) of complete inactivity (sitting) is illustrated on all of the graphs. It shows a more rapid drop in temperature than the periods of minimum activity (slow walking) also illustrated. The period of inactivity affects the slope of the curves. It should be noted that, upon resuming minimum activity (walking), the curves begin to level off.

The 92°F initial temperature reading shown on all of these figures was caused by the excessive heat build-up during the donning of the boots and the arctic clothing. The rapid initial drop recorded in the first 20

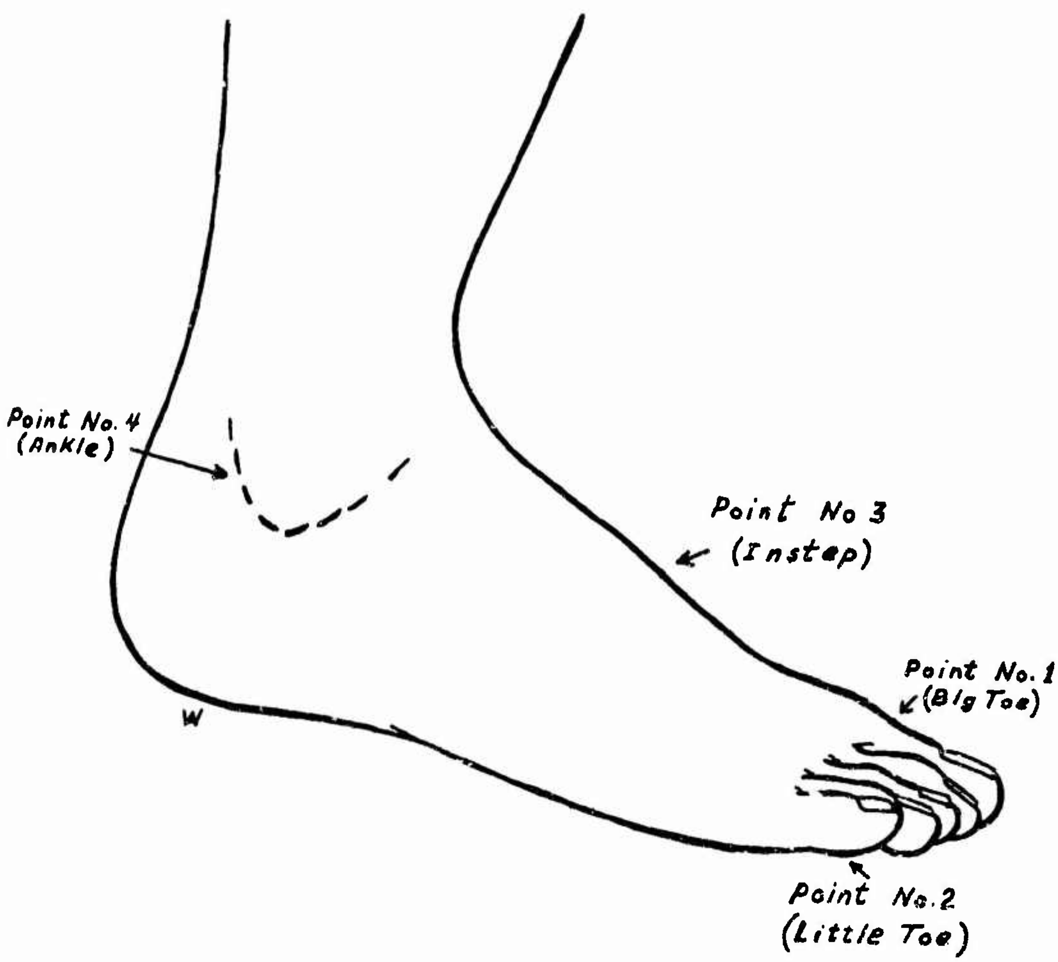

Figure 2. Thermocouple location points

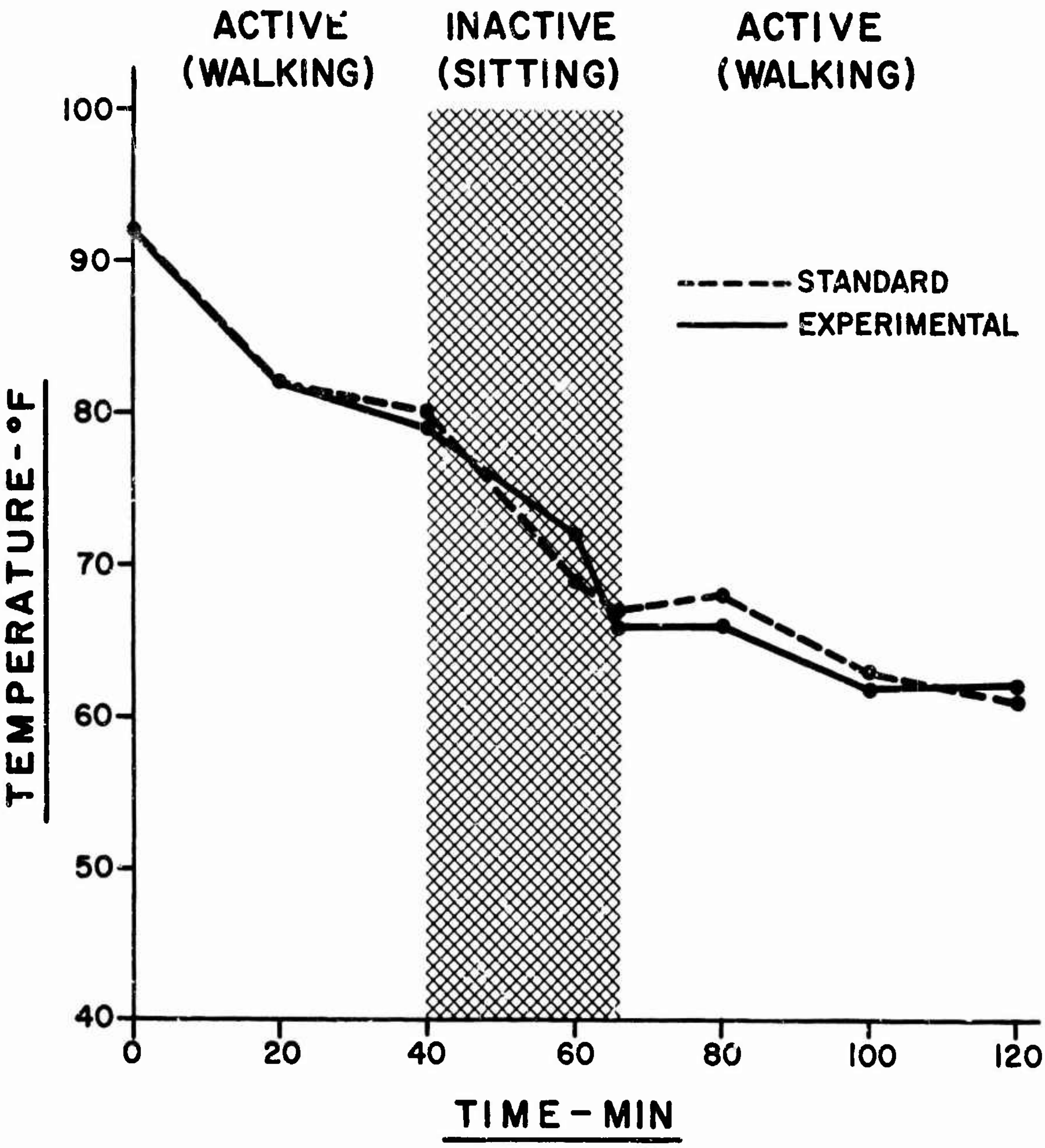

Figure 3. Comparison of Standard and Experimental Insulated Boots
Test temperature -30°F
Thermocouple #1 (big toe)

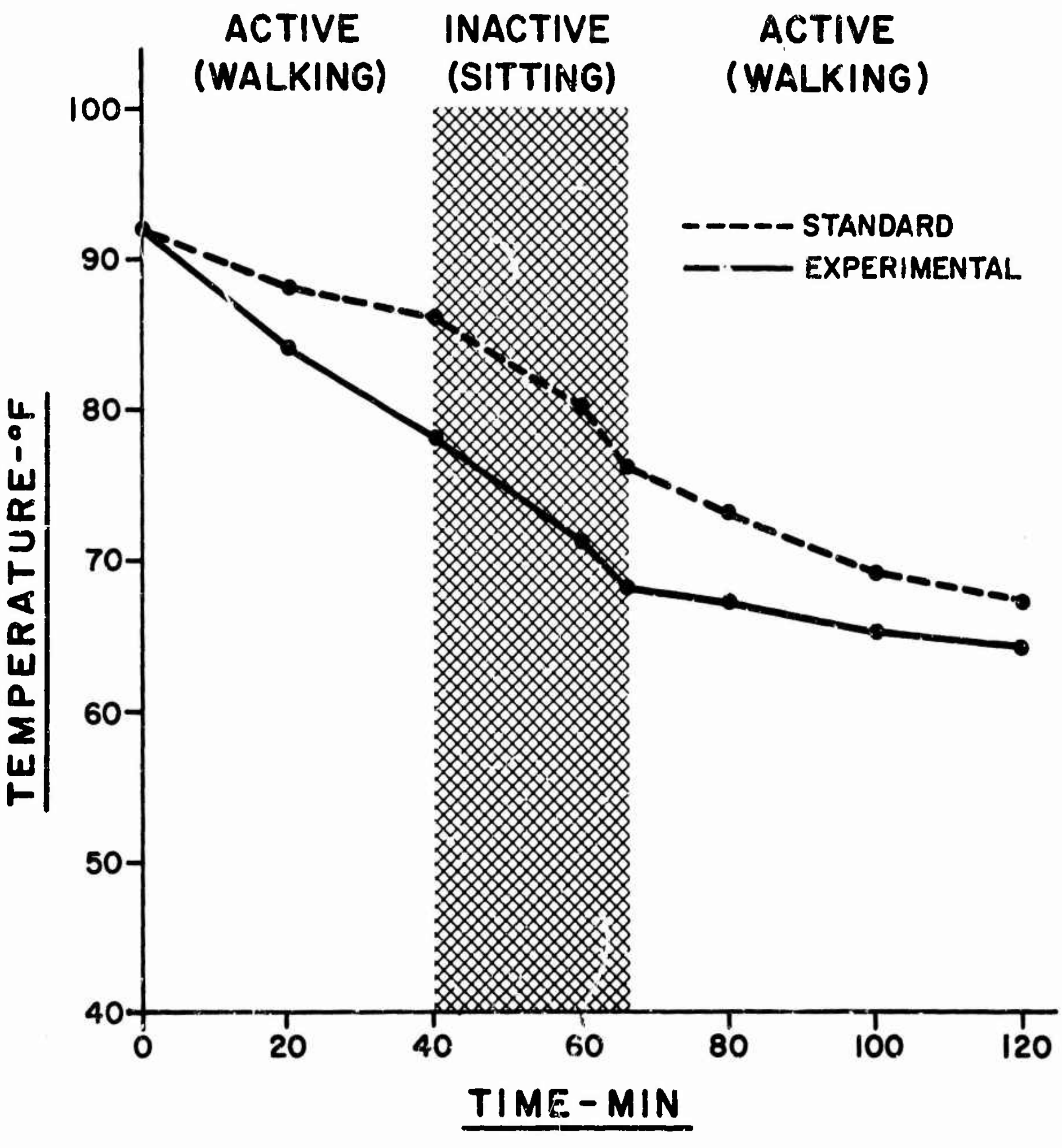

Figure 4. Comparison of Standard and Experimental Insulated Boots
Test temperature -30°F
Thermocouple #2 (little toe)

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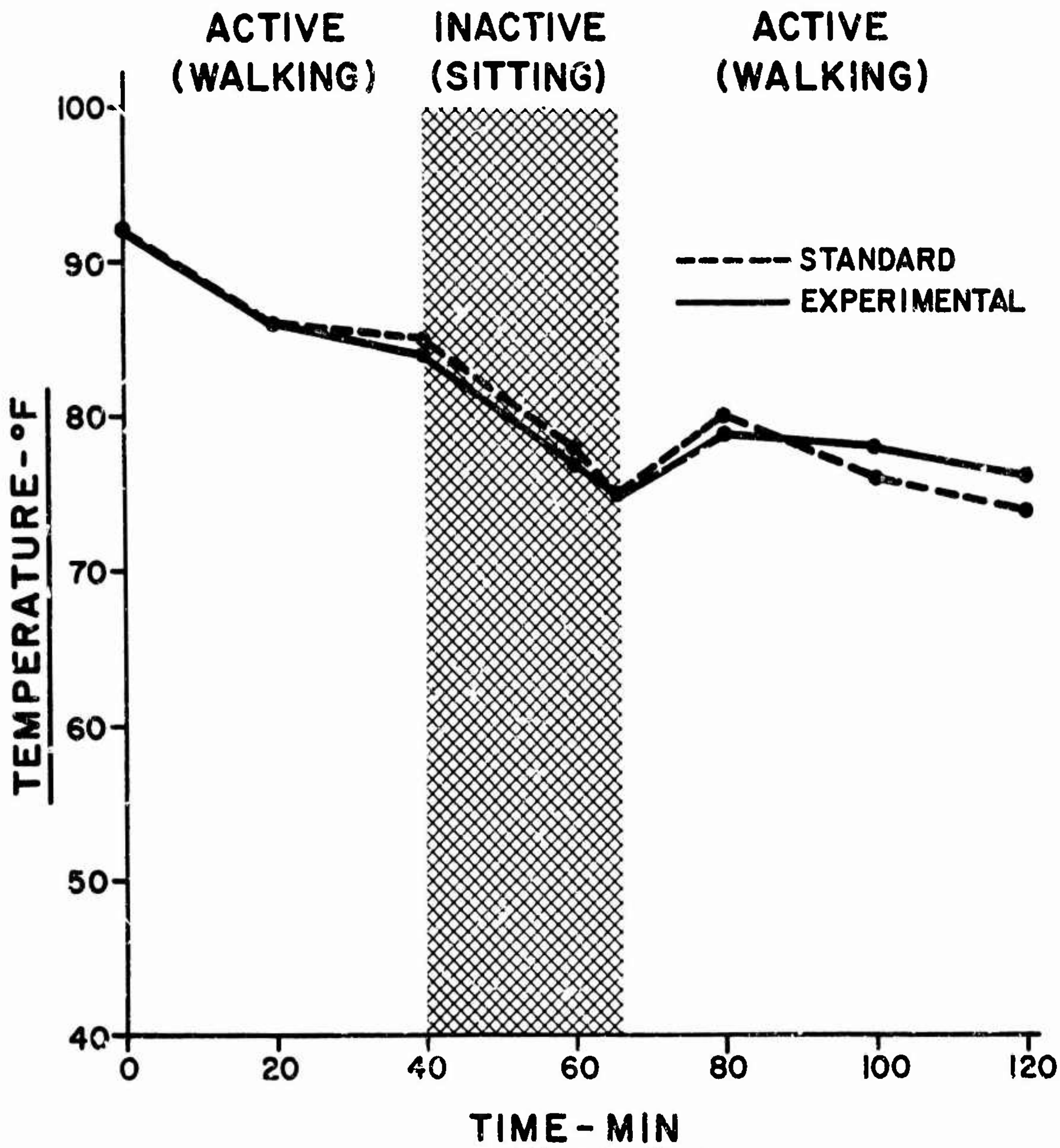

Figure 5. Comparison of Standard and Experimental Insulated Boots
Test temperature -30°F
Thermocouple #3 (instep)

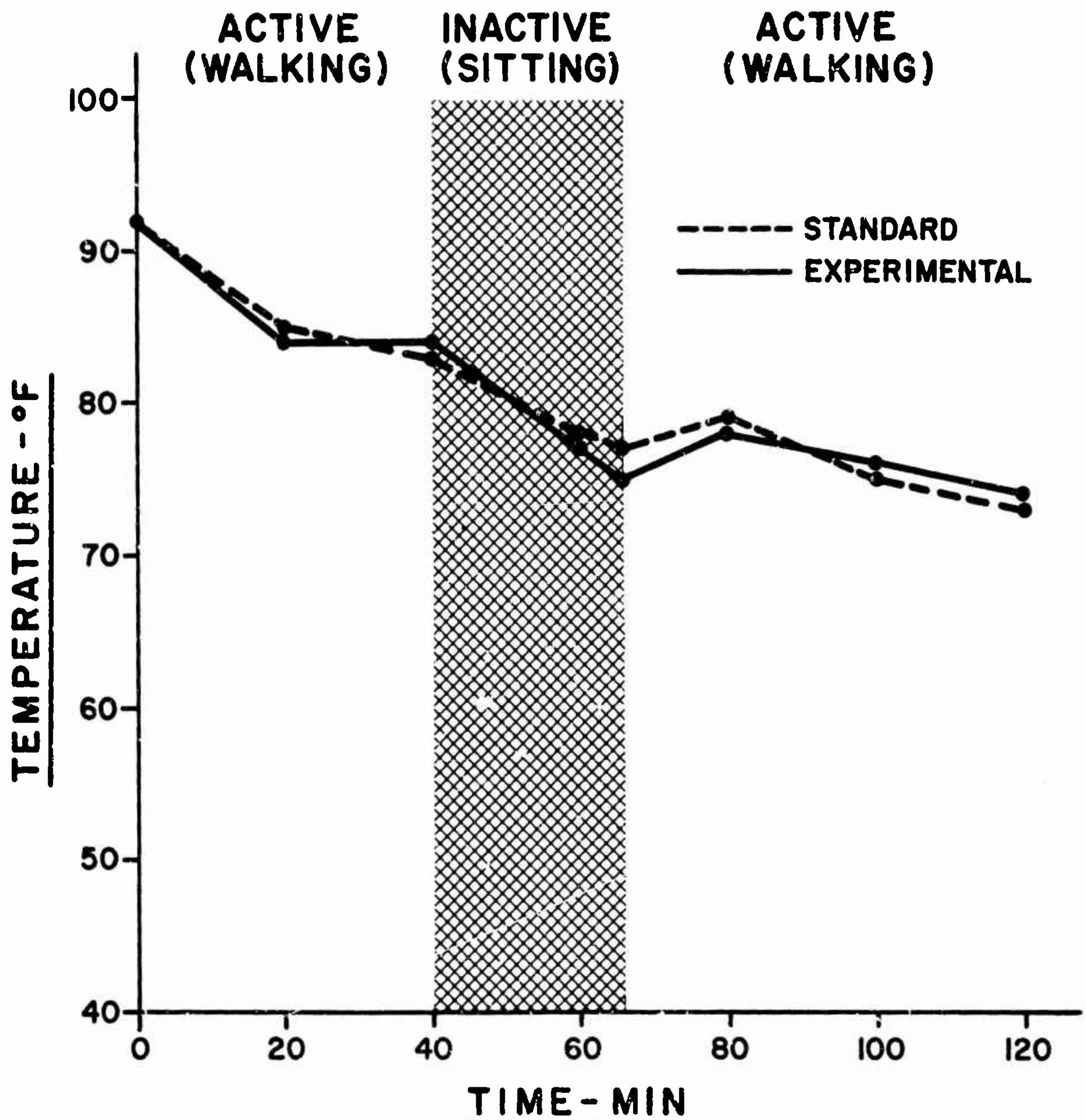

Figure 6. Comparison of Standard and Experimental Insulated Boots
Test temperature -30°F
Thermocouple #4 (ankle)

minutes is not considered significant since this time can be considered as the time required for the clothing ensemble to come to equilibrium.

Table I shows the significant time-temperature relationship between the two boots.

TABLE I

Time-Temperature Relationship at -30°F

	Standard Boot			Experimental Boot		
	20 min	66 min	120 min	20 min	66 min	120 min
Big toe	82°F	67°F	61°F	82°F	66°F	62°F
Little toe	88°F	76°F	67°F	84°F	68°F	64°F
Instep	86°F	75°F	74°F	86°F	75°F	76°F
Ankle	85°F	77°F	73°F	84°F	75°F	74°F

The following was noted during the test:

1. Upon flexing the experimental boot in the toe area, a sharp crease was noted. There were no serious effects and the crease began to disappear slowly when the boot was not flexed.

2. Visual examination of the experimental boot at the completion of the test showed no breaks or cracks in the boot materials.

Conclusion

At the temperatures encountered during this limited test, there was no noticeable difference in low temperature foot comfort between the standard and experimental boot.

The results indicate that the experimental materials, assembled in the form of a boot which weighs only 15.5-ounces, give adequate insulative protection and probably exceed the requirement of providing protection down to -20°F for periods of two hours of inactivity.

APPENDIX B

24 January 1968

Climatic Chamber Evaluation of Low Temperature Properties
of Lightweight Insulated Footwear

1. Objective

The objective of this evaluation is to determine the effect of low temperature on materials, flexibility of construction, donning footwear at low temperature, and on walking ability after footwear has been cold-soaked at -20°F.

2. Test Procedure

a. Two pairs of experimental prototype boots were cold-soaked in the climatic chambers as follows:

Four hours from +20°F down to 0°F, 7-1/2 hours from 0°F down to -20°F, and 6 hours at -20°F.

b. Test personnel wore a single standard cushion-sole wool sock on each foot and the uniform was that for standard cold weather Army use without the long woolen underwear.

c. The boots were donned in the climatic chamber at -20°F after being cold-soaked to determine ease of donning and effect of flexing on boot construction.

d. The treadmill at 3 miles per hour was used to check the walking ability of cold-soaked boots.

e. The prototype boots were worn for one hour at -20°F.

3. Description of Experimental Prototype Boots

a. All-polyurethane integrally cast boot - no shank reinforcement. Weight - right boot: 18.1 ounces; left boot: 17.5 ounces.

b. Polyethylene insulated fabricated boots without leg strap. Weight - right boot: 15.5 ounces; left boot: 14.4 ounces.

4. Test Personnel

a. The all-polyurethane integrally cast boot was worn in the climatic chamber by Mr. Joseph E. Assaf of NLABS.

b. The polyethylene insulated fabricated boot without leg strap was worn in the climatic chamber by Mr. Robert Cargill, also of NLABS.

5. Discussion of Climatic Chamber Test Results

a. The two types of boots had stiffened significantly from cold-soaking in the chambers. The polyethylene insulated fabricated boots were stiffer than the all-polyurethane integrally cast boots. At room temperature the all-polyurethane boots were more flexible than the polyethylene insulated fabricated boots.

b. To evaluate the ease of donning the cold-soaked stiffened boots at -20°F, the test personnel entered the climatic chamber (-20°F temperature) in their stocking feet and immediately began to don the boots from the standing position with the following results:

(1) There was no difficulty in donning the all-polyurethane integrally cast boot. The feet slipped readily and easily into the cold-soaked stiffened boots.

(2) Some difficulty was encountered in donning the polyethylene insulated fabricated boots. Tightness was encountered in the ankle area as the feet were slipped into them. The tightness at the ankle area was caused by the shape of the boot opening. The boot opening was narrow because prior to cold-soaking, the boots were laying flat and the opening was compressed. If necessary, on new boots that have been cold-soaked, the opening can be widened by hand-flexing prior to donning.

(3) No problems are anticipated during donning and doffing of the boots.

c. To check the effect of severe flexing on the cold-soaked boot materials and boot construction, test personnel performed deep knee bends immediately upon donning the boots. This caused severe flexing in the toe area and around the ankles of the stiffened boots. However, there was no sign of failure in materials or construction upon completion of this exercise.

d. To determine walking ability in the cold-soaked boots, a treadmill moving at three miles per hour was used. Walking ability was not impaired by the initial stiffness in the boots.

e. After 15 minutes in the climatic chambers (-20°F), the upper parts of the boots began to return to room temperature flexibility because of generated body heat. Within 30 minutes the toe and heel area began to soften; however, at the end of one hour in the chambers, the boots had not returned to their room temperature flexibility.

f. The climatic chambers were entered in stocking feet and the cold-soaked boots were donned at -20°F. However, there was a lapse of several minutes in the chamber, prior to donning the boots, which resulted in the bottom of the feet becoming cold. Within a few minutes after donning, the feet had warmed up to the point where there was no discomfort from the cold during the one-hour test.

g. A detailed visual inspection of the boots upon completion o. the test indicated no damaging effects.

6. Conclusion

This limited study indicates that cold-soaked boots, when new, can be donned and flexed at low temperature, walked in without impairing walking ability, and suffer no visual effects on materials and construction.

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13. ABSTRACT

The feasibility of producing the first generation of military lightweight insulated footwear using selected materials in a basic pull-on type construction in the weight range of 15-20 ounces per boot was demonstrated. The fabrication of the boots was achieved by two different approaches: (1) by conventional fabrication using the minimum possible number of components, (2) by integrally casting or expanding in place a boot of unified construction. Two prototypes of 50 pairs each were produced on a semi-production basis by conventional fabrication techniques. One prototype used expanded closed-cell polyethylene for upper insulation, the other used expanded closed-cell polyurethane from a millable gum for upper insulation. An additional prototype of 50 pairs was produced by the newly developed integrally casting technique using liquid polyurethane prepolymers. This technique of producing expanded polyurethane insulated footwear offers the greatest potential of meeting the requirements of a lightweight (15-20 ounces per boot), impermeable (water absorption maximum weight 5%), insulated (for service down to -20°F) boots for up to two (2) hours of inactivity.

The integrally cast expanded polyurethane footwear (18-20 ounces per boot), when new, approaches the insulative performance of the standard (black 40-43 ounces per boot) cold-wet boot, but may have reduced durability and service life.

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Design	8					
Fabrication	8					
Tests	8					
Boots (footwear)	9		9			
Insulated footwear	9		9			
Casting	10					
Integrally	0					
Insulation			8			
Polyurethane resins			10			
Cellular plastics			10			

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